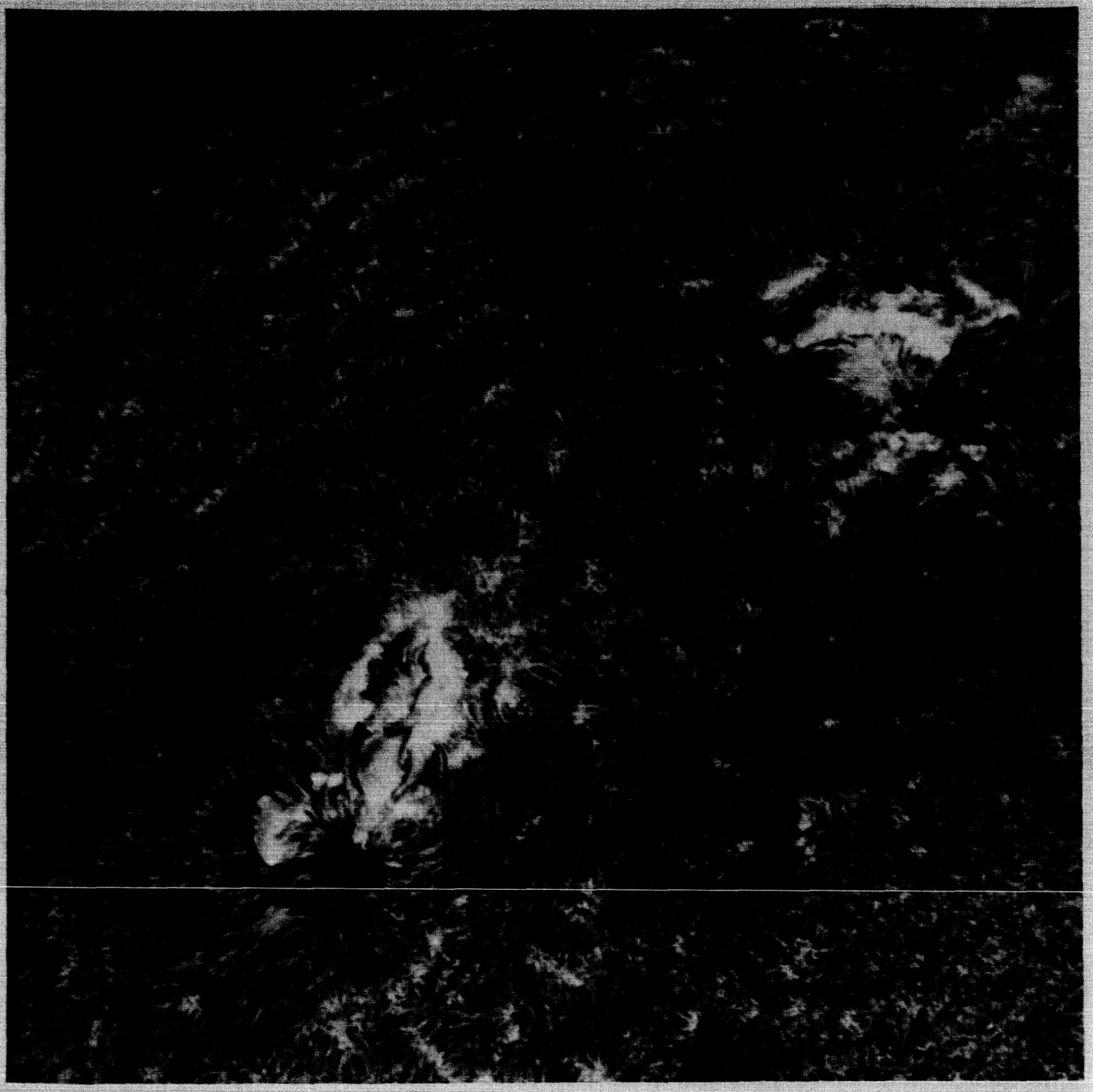

PHOTOHELIOGRAPH

Telescope in Space

COVER ILLUSTRATION: The sun in Hα. Photograph taken with the Carroll spar telescope, Hallé Lyot filter, May 19, 1968, 17:37 UT, shows two sunspot regions, several filaments, and spicules (white "hedge rows" near limb). Courtesy H. Zirin, California Institute of Technology.

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SEPTEMBER 15, 1968

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION.

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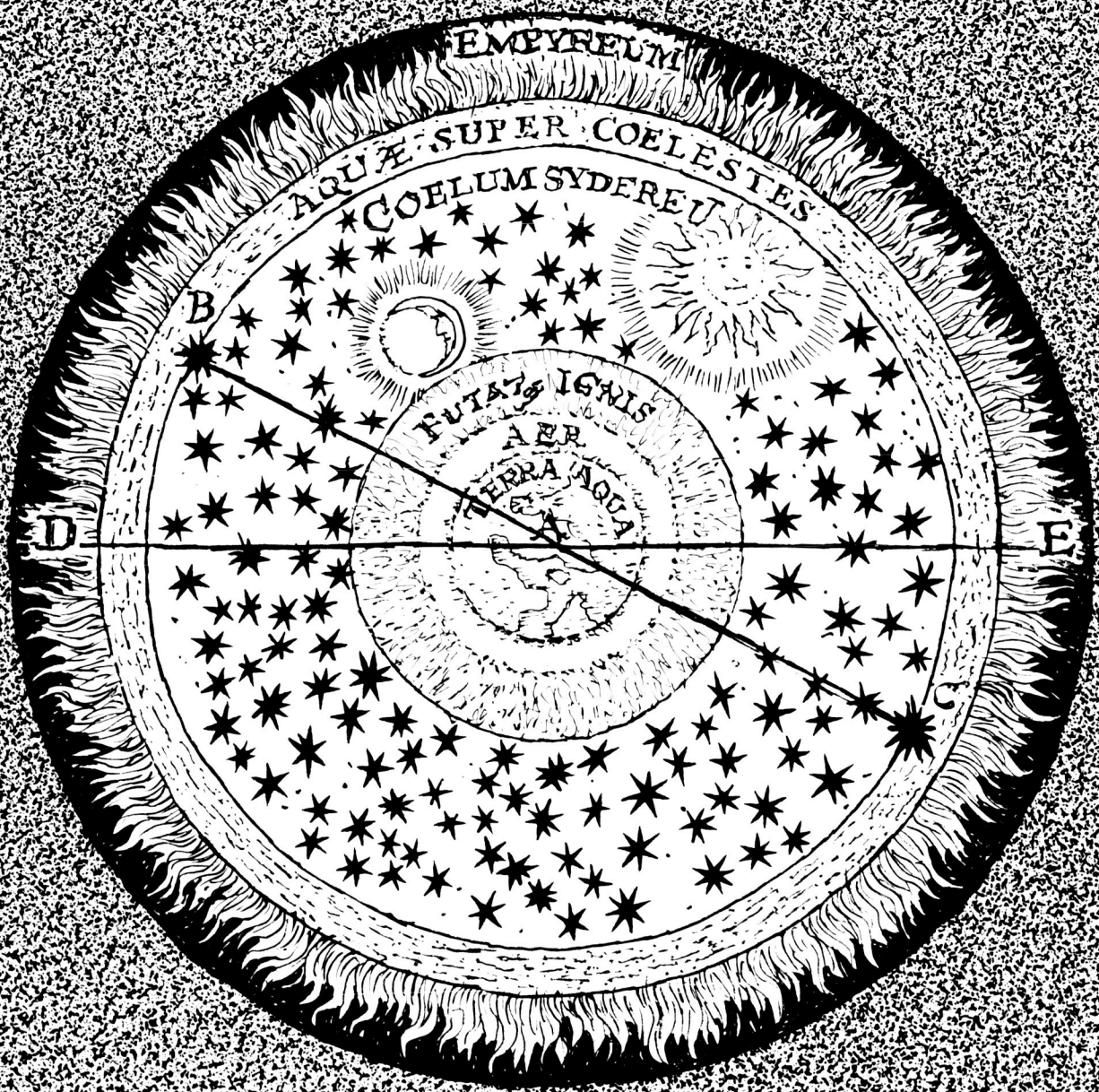
PHOTOHELIOGRAPH

Telescope in Space


EMPYREUM
AQUÆ SUPER COELESTES
COELUM SYDEREUM
B
IGNIS
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TERRA AQUA
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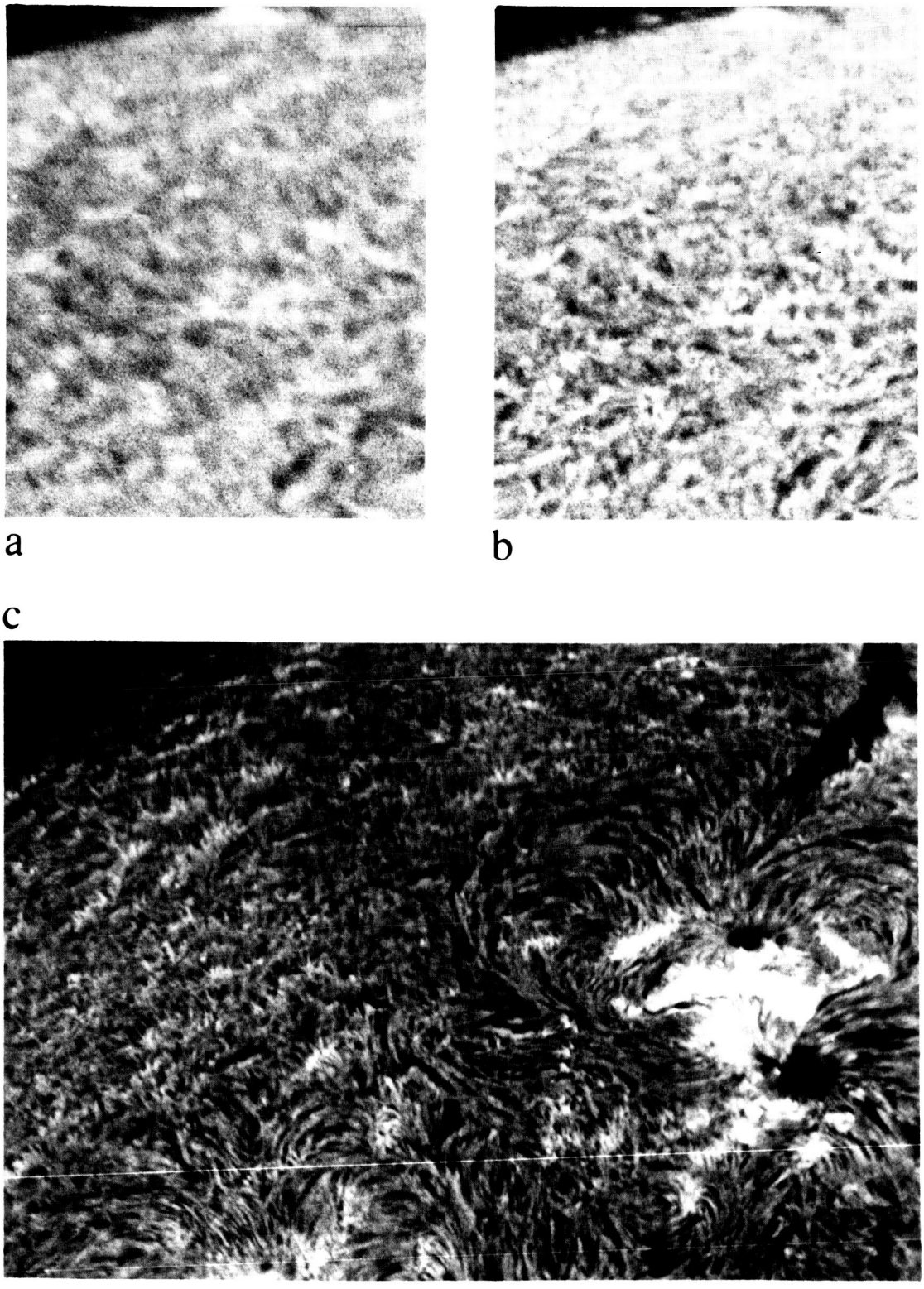
C

OPPOSITE: Pre-Ptolemaic cosmological concept. The sun is one of the two major bodies in the starry layer of the heavens surrounding a central earth. Outer layers of fire and water serve to contain the entire celestial assemblage.

Many advances in astronomical science can be attributed to better observations -- a direct result of higher instrument resolving power. All astronomical observations have to contend with the limitations on resolution imposed by the terrestrial atmosphere, but solar physics has suffered most from the restrictions of the atmospheric veil. Solar physicists are now working at the limits of resolution possible from ground-based instruments. Recent important solar discoveries have resulted from improved resolution obtained with stratospheric telescopes, cinematography, and controlled environment telescopes -- all attempts to circumvent the seeing problem. Future advances in solar knowledge hinge on still higher resolving power, possible only by placing telescopes outside of the terrestrial atmosphere.

For this purpose, the California Institute of Technology, The Jet Propulsion Laboratory, and the Mount Wilson and Palomar Observatories have participated in the development of a Photoheliograph – a large reflecting telescope capable of recording images with film or television in an extraterrestrial environment. The design of the instrument carefully balances potential usefulness against reliability and affords a great chance of success in advancing astronomical knowledge through superior observation.



Clumps of spicules near the solar limb.

(a) Poor seeing

(b) Good seeing, same region seen 40 seconds earlier

(c) Same region under extraordinarily good seeing conditions

The assumption that solar physicists can resolve 1/2 second of arc from the ground does not take into account the hundreds of photographs that we have to search through for the one or two that exhibit this quality of seeing. The enormous inconsistencies in seeing quality are shown by the three photographs on the facing page. The photograph on the right (b), taken in a moment of good seeing, shows far more detail than the picture on the left (a), taken only forty seconds later. Photograph c, also shown on the cover, includes the same region under extraordinarily good seeing conditions on the same day.

A telescope in space is potentially able to provide a large gain in resolution over the best ground-based observations. Equally important, this improved resolution will be consistently high throughout the forty or more minutes of each earth orbit when the telescope is in sunlight. In the past, each advance in our ability to see fine details of solar activity has greatly expanded our understanding of the solar atmosphere.

Galileo built the first telescope capable of resolving sunspots. Our present knowledge of the solar atmosphere owes much to the systems built by Hale – the first ones consistently able to resolve and spectrally analyze solar structures subtending an angle of a few seconds of arc. The study of the sun is now at the limits of resolution possible under our atmospheric constraint. True, successful and important ground-based work employing intricate auxiliary equipment is now in process, but if solar physicists are to untangle the complexities of sunspots, flares, granulations, and other small-scale phenomena, they will need improved resolution. It is reasonable to expect that our Photoheliograph will lead to advances in knowledge as great as those that historically accompanied improvements in resolving power.

The problems that can hopefully be solved are many. For example, the evolution of a sunspot group, particularly in its infancy, is still a mystery. The ground-based observer needs unusually good luck to observe the rapid changes with good seeing. Our Photoheliograph would not have to trust to luck to observe sunspot development.

The evolution of granules, patterns observable in white light and presumed to be convection cells, can at present be observed only for a matter of minutes with the greatest difficulty by selecting from thousands perhaps a few dozen photographs with good seeing. Even so, we cannot resolve the dark lanes that separate the granules and Leighton (1) has shown that the lanes lie at the limit of present resolution.

To understand the solar convection, we need to resolve features the size of the scale-height of the atmosphere – some 150 km. A Photoheliograph with 0.2 arc-sec resolution can accomplish this feat.

Wavelengths below about 0.33μ cannot penetrate the atmosphere, but our Photoheliograph can see radiation in the near-ultraviolet – one of the chief incentives for orbiting the instrument in space. Taking a number of pictures of the sun with broad-band filters in several regions of the near-ultraviolet will be a large step beyond current observations. The best extant pictures in the near-ultraviolet spectral region have resolutions of some 5 or 10 arc seconds (2).

Moreover, since all work so far has been done only in integrated light, there exist great possibilities for work on individual features in the light of single spectral lines. An example is the important possibility of taking pictures in the C IV λ1550 line of study the hotter components of flares.

Many forms of chromospheric activity can be studied by adding a filter to select a narrow band such as hydrogen-alpha (Hα). The photograph on page 2 shows some of the significant structures seen in a flare with normal ground-based seeing. Films with high-quality resolution have greatly improved our knowledge of flares

Flare, January 14, 1968 (fair seeing conditions). The arrow indicates a small globule that is being ejected from the region at high velocity. Such energetic but hard-to-see events may contribute significantly to the x-ray and radio emission of flares. Photographs taken in the center of the Hα line at Robinson Laboratory, California Institute of Technology.

in recent years, but theory indicates that the initial release of energy may occur in a region less than a few hundred kilometers across. We need better than ground-based resolution to locate and study this triggering phenomenon. We also need higher resolution to discover any permanent small changes that may accompany a flare, since the energy released in a flare is much less than that available in the entire sunspot region.

Although spicules can be detected both on the disc and at the limb of the sun (cover and photograph on page iv), their nature remains unknown. Observations with a resolution of 0.2 arc-sec over a matter of tens of minutes will allow detailed study of their internal structure (if any) and their means of growth and decay.

The possibility of observing motion of material into the corona is of more than passing interest as this material presumably is destined to become the solar wind.

There are many other features worth studying in fine detail. But more important may be the opportunity to study those unnamed structures that are now only dimly glimpsed in moments of extraordinary seeing.

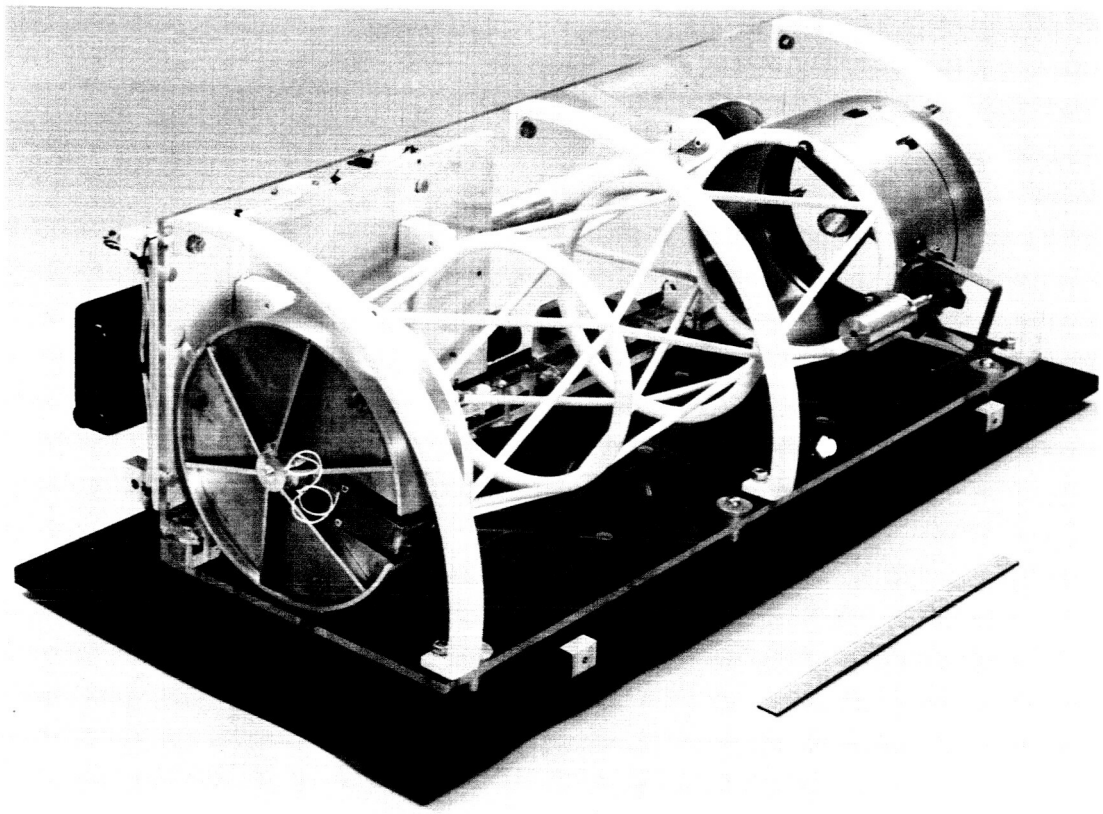
Aside from the obvious benefits derived from visual inspection of photographs taken with our Photoheliograph, the instrument can also provide monochromatic pictures taken on two sides of a spectral line that can then be compared to yield maps of the solar magnetic field (from the Zeeman effect) and velocities along the line of sight (Doppler effect).

The 26-in. aperture of the Photoheliograph will gather sufficient ultraviolet and Hα light to allow short exposure times (10^{-1} - 10^{-2} sec) or relatively fast TV scanning rates. The diffraction of a smaller aperture would prevent getting 0.2 arc-sec resolution; on the other hand, a considerably larger aperture telescope probably cannot be designed successfully with the current spacecraft constraints (i.e., Apollo Telescope Mount spacecraft).

REFERENCES

1. Leighton, R. B., Ann. Revs. Astron. Ap. 1966

2. Blamont and Carpentier, Solar Physics 1, 180; 1967

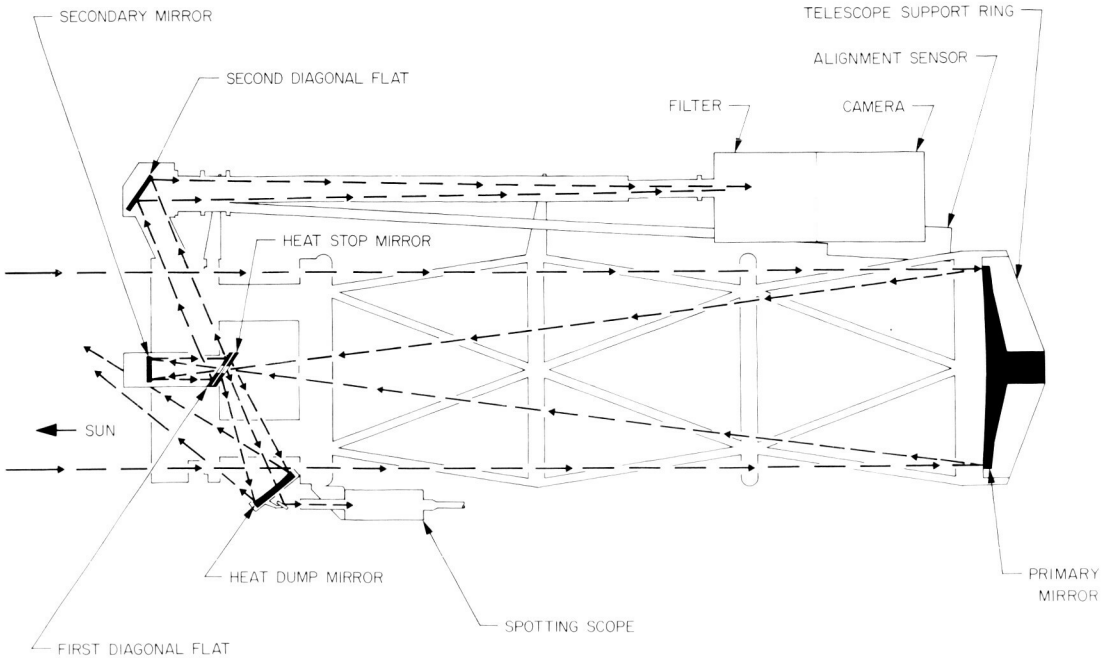


Photoheliograph, quarter-scale mockup

PHOTOHELIOGRAPH SYSTEM

Subsystems

- Telescope
- Image Data Recording
- Filter
- Temperature Control
- Instrument Operation



■ *Photoheliograph*

DESIGN

Although the technology developed is applicable to manned as well as unmanned space missions, the Photoheliograph design is compatible with the Apollo Telescope Mount "A" spacecraft and can also be adapted to the Apollo Telescope Mount "B" solar mission. Regardless of future spacecraft design modifications, the instrument design constraints, based on the Apollo Telescope Mount A spacecraft, will remain valid.

The thermal and mechanical constraints are the most demanding. The length constraint -- 123 in. with a 26-in. aperture primary – requires a rather high secondary magnification of 13. To achieve near-diffraction-limited performance, tight mechanical tolerances must be maintained in addition to high-quality ($\lambda/50$ RMS error) mirror figures. In-flight alignment and focus mechanisms are therefore included in the instrument design.

The thermal constraint of less than 0.6 BTU per hr (0.2 w) heat input to the spar proved to be a major problem. Active fluid cooling is used to prevent an objectionable temperature rise of the primary mirror due to solar heating and to prevent heat flow to the spar. Since the only way to reject heat is by radiation to the 50°F canister, all the area available in one quadrant as well as part of another quadrant must be used. Very little heat is rejected from the mouth of the telescope since the primary mirror is a poor radiator and the instrument will most likely be pointed towards earth on the dark side of the orbit.

The entire Photoheliograph, except for the operation console, will be located in the Apollo Telescope Mount canister. The instrument operation will be controlled by the astronaut from the Apollo Lunar Module.

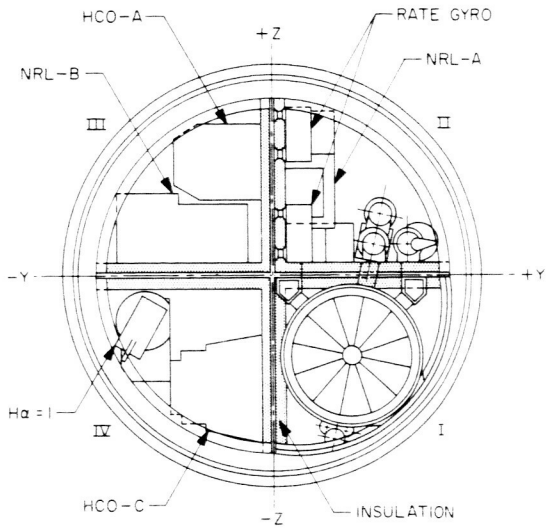
DESIGN CONSTRAINTS

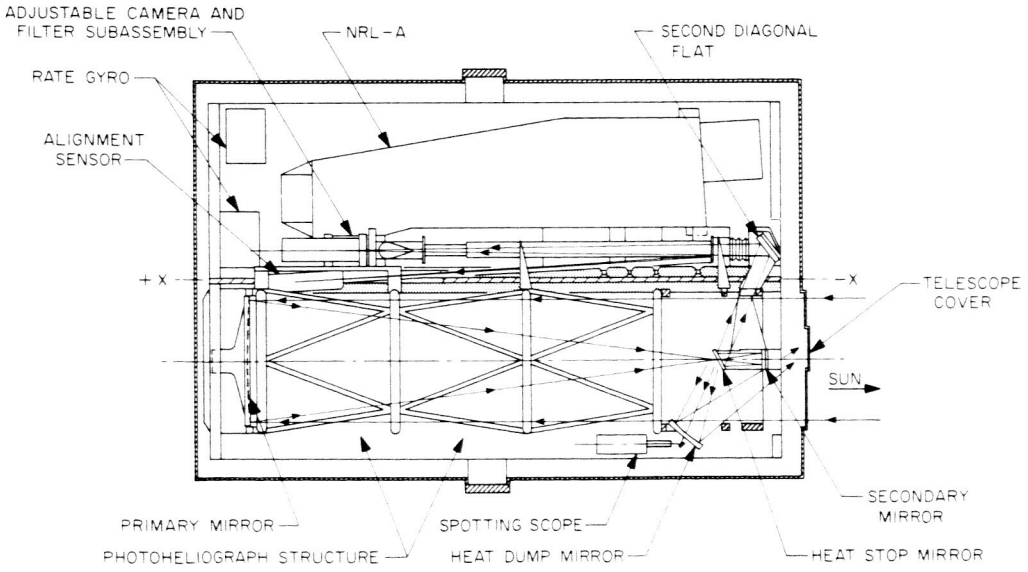
Mechanical
- Weight: 700 lb per spar quadrant
- Envelope: one complete quadrant and a portion of another; max length -- 123 in.

Electrical
- Power: 150 w average consumed
- Compatibility: electro-magnetic

Thermal
- Spar operating at 70°F ±3 with a 50°F ±3 canister wall for thermal control
- Heat conducted to spar: less than 0.6 BTU per hr
- Radiation view to space: none

Pointing
- Jitter rate: less than ±1 arc sec per sec
- Drift: ±2.5 arc sec per 15 min (pitch and yaw); 7.5 arc min per 15 min (roll)





OPTICS TEMPERATURE CONTROL

The instrument is designed to provide a high-quality image (near diffraction limit) with a 3.2 arc-minute field of view and resolution to 0.2 arc-second over an 18 x 24mm format at the recording (focal) plane. The energy is separated into three spectral regions by a combination of beam splitters and filters and subsequently recorded on either film, television, or a combination of both.

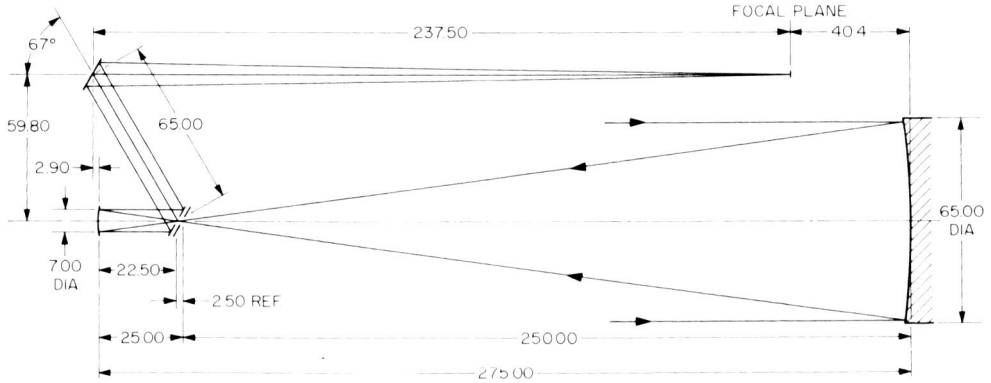
The temperature control subsystem conducts heat from the primary and secondary optics to maintain accurate mirror figure and avoid conduction to the Apollo Telescope Mount spar and other instruments. A combination of active and passive elements will be used to provide overall instrument temperature control.

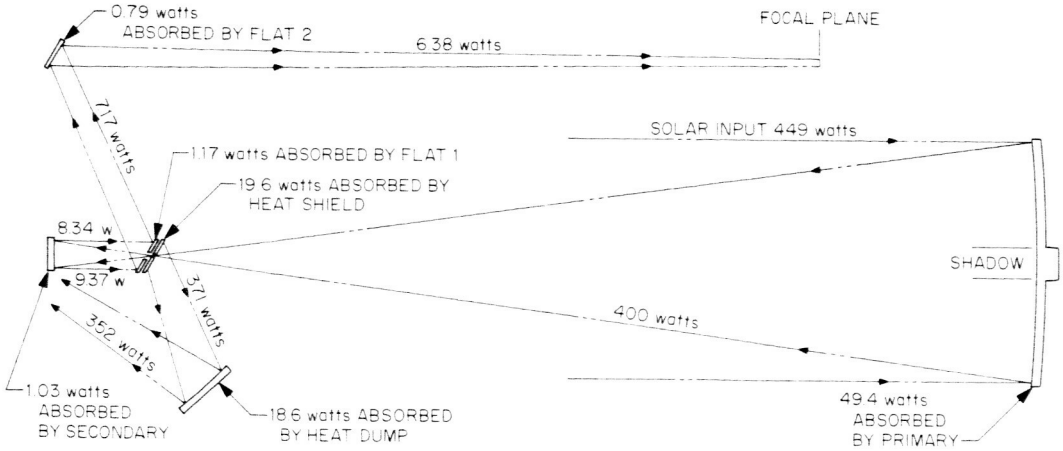
The telescope design makes maximum use of a single Apollo Telescope Mount "A" canister quadrant. The largest primary aperture that can be accommodated, allowing for structural items, is 0.65 meter. The most serious design constraint is the thermal control of the instrument both from an internal degradation point of view as well as from the effect on the Apollo Telescope Mount system and other instruments. From the thermal point of view, therefore, a modified Gregorian design was selected, the principal features of which are the uniform illumination of the primary mirror and the disposal of 90% of the energy in the reflected beam by the heat stop mirror, located at the primary mirror focus. Since the optical elements in the image-forming path other than the primary are now protected, satisfactory performance can be obtained using a low-expansion material such as Owens-Illinois Cer-Vit. The only image-forming element requiring special attention is the primary mirror.

Since the Photoheliograph is attached to the spar, heat flow from the instrument must be well controlled. It has, therefore, been decided to use an actively cooled primary mirror by circulating a fluid through the mirror blank and radiating the heat to the 50°F Canister wall. The mirror figure is also maintained by this scheme.

A number of materials were considered for the primary mirror; the best candidates were the low-expansion glasses: Owens-Illinois Cer-Vit and Corning ultra low expansion (ULE) fused silica. The Corning ULE material was selected as it is possible to fabricate a mirror with internal cooling channels by fusing together the two parts of the blank.

Once the optical elements have been specified and designed, the next step is to insure that they can be assembled and maintained in

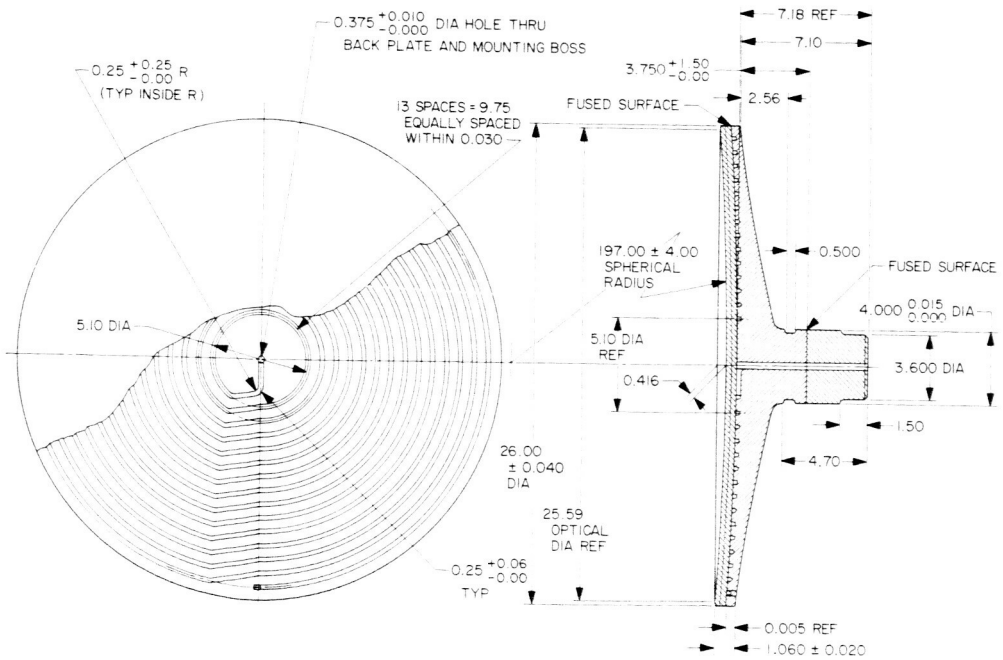




■ *Heat flow*

position to withstand the launch and operation environments. In order to obtain diffraction-limited performance from the optical system, provision will be made for in-flight alignment and focus. The optimum focus will be selected by remote positioning of the camera package from the Apollo Lunar Module and sensing focus by a closed circuit television system.

In order to compensate for disturbing thermal effects, alignment must be performed while the instrument is collecting sunlight. It is therefore necessary to use a secondary optical path to prevent interference from the solar beam. The path selected is that contained in the shadow areas caused by the secondary mirror. An autocollimating technique is used for tilt



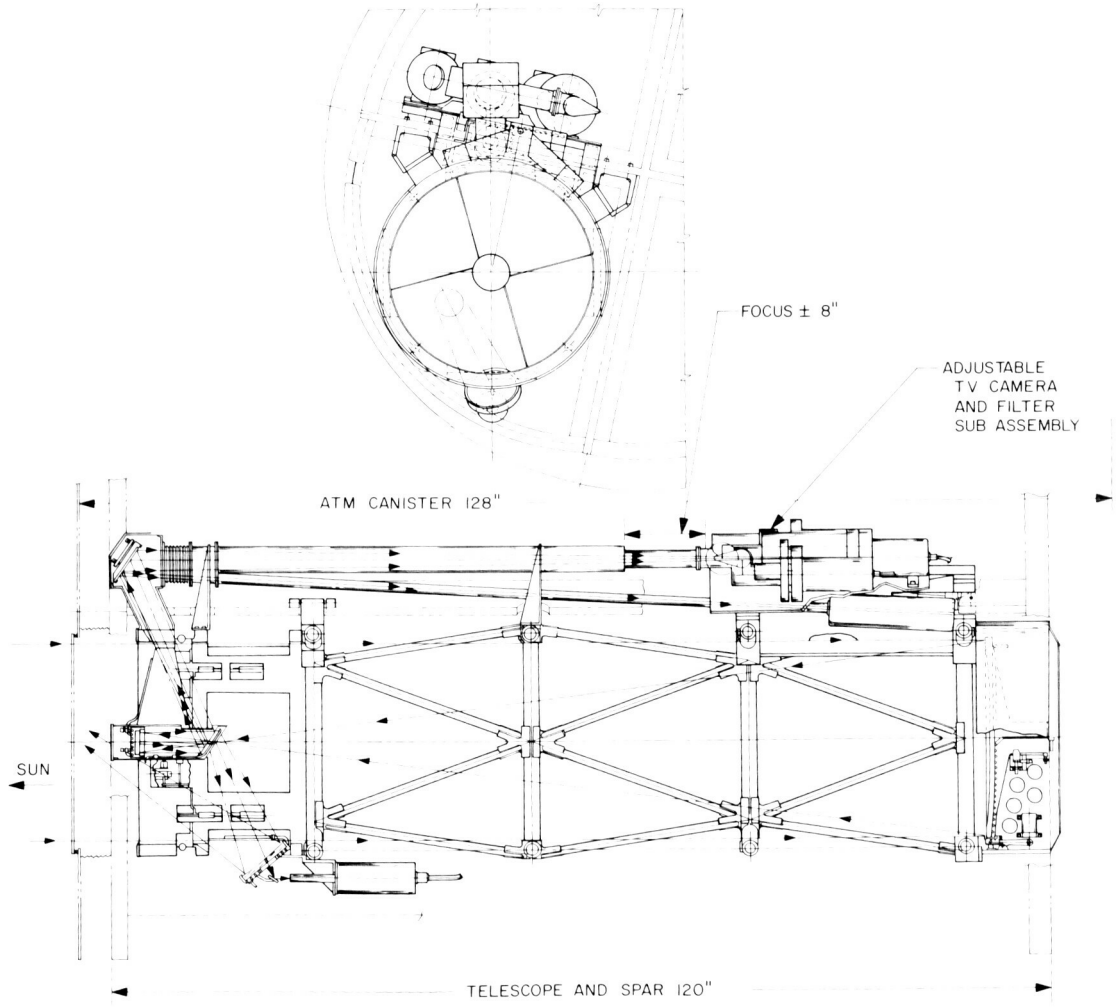
■ *Primary mirror blank showing cooling channels*

realignment and a boresight method for decentration. The alignment will be accomplished by moving the secondary assembly with respect to the primary assembly. The alignment sensor and primary mirror will be assembled as a temperature-compensated rigid body.

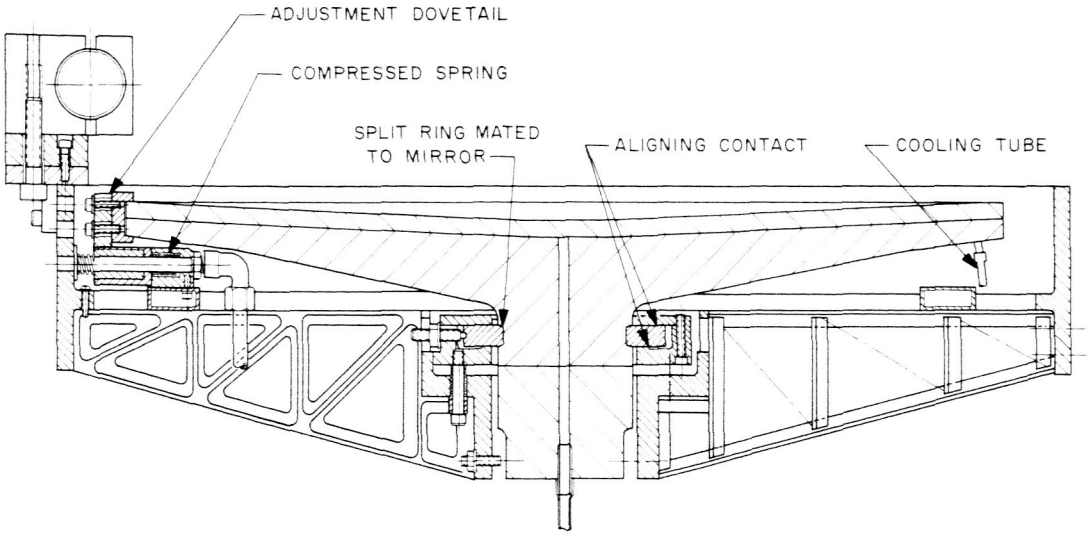
STRUCTURE

The telescope structure has been designed using a truss arrangement. The open truss was selected to avoid an objectionable acoustical problem (organ pipe effect) associated with a closed tubular configuration, even though this closed arrangement appeared better from the viewpoints of weight versus strength and thermal isolation.

Design emphasis to date has been on the primary mirror assembly. The mirror is held at the central hub during the in-flight operation and supported at the edges during launch and docking modes. The mirror edge launch locks are relaxed to avoid distortion when the instrument is placed into operation.



■ *Structure showing truss arrangement*



■ *Primary mirror assembly*

IMAGE DATA RECORDING

The image data will be recorded with three separate camera packages to provide simultaneous recording capability in the three spectral regions (UV, white light, and Hα). The camera subsystem will be contained in an adjacent quadrant and mounted to the telescope through the spar. The data can be recorded by either film cameras or television cameras operating in conjunction with real-time communication to the ground or with tape recording in the Apollo Lunar Module. The Rayleigh optical resolution limit of 33 line pairs per mm at the recording plane is sufficiently close to TV imaging system capabilities that serious consideration is warranted.

The film camera data capacity per frame far exceeds the requirements, but the number of frames that can be used and therefore the total mission data are limited by the amount of film that can be carried and replaced by extravehicular activity (EVA). The TV approach, on the other hand, is limited only by the communication system down-link capacity and onboard data storage.

The TV approach offers a considerable operational advantage since EVA is eliminated, and the astronaut can perform a real-time evaluation of the data to insure that satisfactory data are being recorded. He will also be in a position to make changes such as shutter time, focus, and camera voltages to compensate for changing conditions. Photometric accuracy can be preserved by immediately digitizing the data, thus eliminating the unwanted effects of various analog transfer functions acting on the data.

As far as the TV camera is concerned, two areas need attention. First, the storage vidicon has marginal sensitivity in the Hα region of 6563Å due to the properties of the photoconductor. Second, the required resolution of some 1600 lines in a tube having a format capability of 22 x 22 mm is not commercially available. Laboratory tubes of this resolution and format capability, however, have been demonstrated. The most promising device to achieve the sensitivity required at Hα is the image intensifier vidicon. This field is currently receiving considerable attention from industry.

OPERATION CONSOLE

A console located in the Apollo Lunar Module will be provided for the astronaut who will be trained to operate the instrumentation as well as to make judgements regarding pointing and data recording. Routine operations such as thermal control system activation and power cycling will be placed on a timer system in order to allow the astronaut to concentrate on data recording. It is expected that alignment and focus will have to be monitored and adjusted occasionally during photography. TV displays will be provided to allow real-time analysis of the quality of the data being recorded. Override systems will be provided to allow the astronaut to manually control the automated portions of the instrument in the event of a malfunction.

TEST AND OPERATIONS

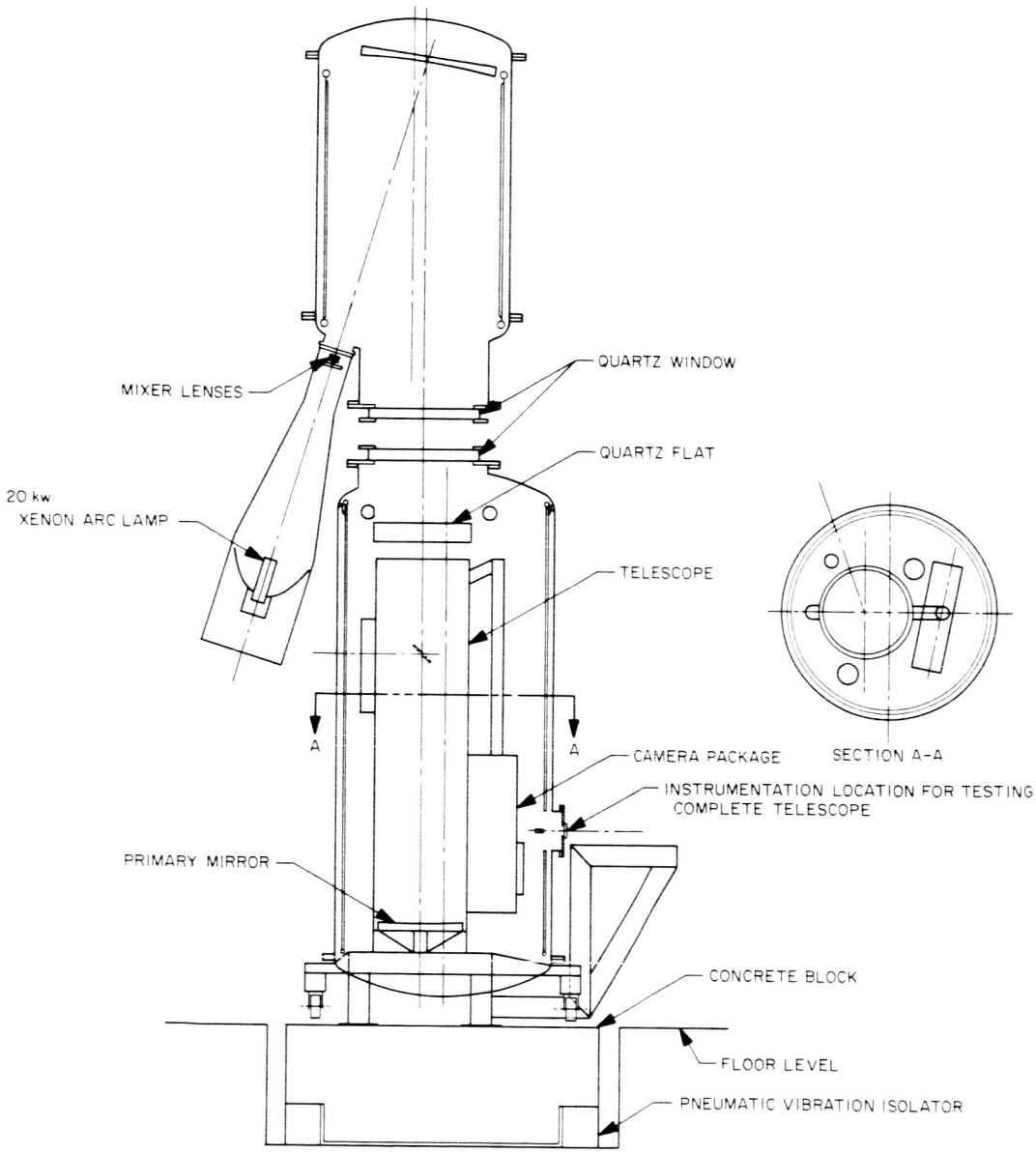
In order to verify that the instrument performs as designed, a test capability must exist to measure diffraction-limited performance under a simulated operating environment. This implies that the test instrumentation must be capable of quantitative optical path difference system measurements to $\lambda/20$ and component measurements to $\lambda/50$. Since the system will be operating under dynamic thermal and mechanical conditions, performance must be measured under these conditions.

For this reason, the laser unequal path interferometer manufactured by Itek Corporation has been chosen. The interferometer is capable of accurate high-speed measurements, with the interferogram being recorded on photographic film. The ability to perform these measurements is strongly dependent on the test environment and the stability of the instrument under test. The two conditions that give rise to errors and noise are mechanical vibrations of the optics with respect to the interferometer and optical path disturbance caused by thermal gradients. The thermal problem is dealt with by the use of a vacuum system. In order to minimize the vibration problem, the test apparatus, which will consist of the telescope, interferometer and vacuum system, will be mounted on a seismic mass which is isolated by a pneumatic isolation system. The effects of vibration can be further reduced by fast shutter times when recording the interferogram. In order to simulate the operating environment, a solar beam will be introduced to illuminate the telescope.

STATUS

Considerable effort has been devoted to the design and analysis of the primary mirror as the key system component. This analysis has included optical performance under static and dynamic thermal loads and 1-*g* static loads for a number of different materials and configurations. The mirror blank design is complete and ready for fabrication. Optical analysis programs have been developed to do computer ray tracing of the system both aligned and misaligned to obtain mechanical design tolerances. The optical performance has been related to modulation transfer functions (MTF) at the exit pupil, taking all elements in the image forming path into account. MTF's and single valued "Strehl" ratios have been computed for the entire optical train, taking into account mirror figures and misalignments.

Preliminary mechanical design has been completed and rigorous structural analysis has begun. Detailing of the primary mirror assembly is in process with completion scheduled by the end of the calendar year 1968.


MIXER LENSES
QUARTZ WINDOW
QUARTZ FLAT
20 kw
XENON ARC LAMP
TELESCOPE
A
A
CAMERA PACKAGE
INSTRUMENTATION LOCATION FOR TESTING
COMPLETE TELESCOPE
PRIMARY MIRROR
CONCRETE BLOCK
FLOOR LEVEL
PNEUMATIC VIBRATION ISOLATOR
SECTION A-A

Reference Documents

A series of documents published by the Jet Propulsion Laboratory contain detailed discussion of the Photoheliograph.

Primary Mirror Development	750-7	Alignment System	750-11
Optical System	750-8	Structure, Mounting, and Mechanisms	750-13
Optical Test Chamber	750-9	Test and Operations Plan	750-15
Optical Testing	750-10		

CONCLUSION

It is only a matter of time until every branch of physical astronomy stands confronted by the limits of resolving power dictated by our atmosphere. If our understanding of the universe is to continue to expand at the present rate, it is inevitable that more and more telescopes will have to go into space. The construction and operation of our Photoheliograph will provide invaluable experience for that endeavor.

The benefits to astronomical science derived from every step of orbiting a complete observatory are many. The high resolution alone should solve many of the problems of solar atmosphere morphology. High resolution in monochromatic light will give us great flexibility in determining velocity and magnetic fields as well as temperatures and other significant factors. High resolution combined with spectroscopy will present even greater possibilities.

In deciding on the achievement level which we can hope to attain in the near future, reliability has to be balanced against potential usefulness in the light of a realistic assessment of available resources and the state of the art. Our Photoheliograph, with its aperture calculated for optimum observation and its superior monochromatic capability, represents the greatest stride that we can presently attempt with a high probability of success.

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